Briefing note for the Scientific Strategy discussion

Disclaimer: This document is meant to facilitate discussions.

1. Scope:
- To execute a world-class, deep-underground liquid argon neutrino experiment for long baseline neutrino oscillations, neutrino astrophysics and proton decay searches.
- Data-taking with a large initial mass starts around 2025 and extends beyond 2035.

2. Science goals:
- The physics case is compelling and competitive, and aims for measurements with unprecedented precision. LBNF has a high probability to discover new phenomena and to expand frontiers with scientific capabilities such as:
  ➡CP Violation in neutrino sector (CPV):
  - Precise measurement of the last unknown parameter of the PMNS matrix, thereby completing the measurement of all parameters of the matrix.
  - Discovery of a new source of violation of a fundamental symmetry of nature.
  - Inform models (e.g. leptogenesis) which give an explanation of the observed matter/antimatter asymmetry in the Universe.

  ➡Matter effects and Neutrino Mass Hierarchy (MH):
  - Study of the matter effects on neutrino and antineutrino oscillation probabilities, a key element and precursor of CPV measurements.
  - Determination of MH by a straightforward comparison of neutrino and antineutrino running mode (swapping focusing horn polarity).
  - Providing important input (NH vs. IH) to test GUT models, and to guide $0\nu\beta\beta$ decay searches.

  ➡The Three-Flavor Paradigm:
  - Detection of all oscillation channels: $\nu\mu$ disappearance, νe and $\nu\tau$ appearance.
  - Precision measurements of all fundamental mixing angles, and θ_{23} octant resolution.
  - Independent measurements of parameters for neutrinos and anti-neutrinos. Verification of CPT.
  - Over-constraint of the PMNS matrix.
  - Test of non-standard interactions (test of anomalous propagation through Earth).
  - Sterile neutrino searches.

  ➡Neutrino astrophysics:
  - Study of atmospheric neutrinos (complementary oscillation measurements) with exclusive final states reconstruction (NC/CC, tau).
  - Detection of supernova burst with flavour discrimination and particular sensitivity to νe. Detection of neutronisation signal.
  - Constraints on new extraterrestrial sources of neutrinos.

  ➡Nucleon Decay:
  - Direct test of GUT

  ➡Collection of high statistics neutrino interactions (near detector(s)):
  - Phenomenology and modelling of neutrino interactions in the GeV range
  - Exclusive cross-sections
  - Rare processes
  - Nuclear physics

3. Configuration parameters:
- The science goals can be reached with various configurations of experimental setups.

- HyperK is a giant Water Cerenkov detector located at 300km distance from J-PARC with an off-axis beam peaked around the first oscillation maximum. HyperK determines δ_{CP} by precisely measuring the ν/νbar asymmetry. The MH must be known to interpret the measured ν/νbar asymmetry in terms of δ_{CP} phase and CPV. HyperK relies on its measurement of atmospheric neutrinos to determine MH and/or on external input.

- LBNF is based on the liquid argon technology and adopts a set of configuration parameters to execute the science in a complementary way to HyperK.

- The list of configuration parameters comprises:
  (a) The nominal neutrino beam power
  (b) The nominal detector mass
  (c) The baseline
  (d) The beam energy profile

- The configuration parameters are fundamental variables that affect the performance, the costs and the timescale of the project.

- The choice of Homestake as far site defines a baseline of 1300 km. Alternative sites should be at a distance somewhere between 2000 and 2300 km. The search for an alternative site in a "green field" and/or with horizontal access is likely to give the largest number of options. The approval and authorisation process of a new site might introduce delays. Top-down guidance, taking into account realism, political aspects, etc., will influence the choice of the site.

4. Scientific Priorities and Strategies

- The configuration parameters are defined according to scientific priorities and an adopted strategy.
- The scientific priorities and the strategies comprise the following items:
  - Priority of determining of δ_{CP} via spectral shape behaviour relative to measurement of ν/νbar asymmetry.
  - Priority of mass hierarchy measurement on a competitive timescale.
  - Strategy for phased/incremental approach to achieve physics goals given funding or technical limitations on the overall program schedule.
  - Priority of astrophysics (non-accelerator programme).
  - Priority of non-oscillation near-detector physics vs. far-detector physics.

5. Preliminary considerations on MH and CPV:

- The sensitivity of the LBN programme scales roughly as **exposure**, defined in kt*MW*year, where a nominal year of running is assumed for the accelerator. See Table 1.

Exposure (kt.MW.yr)	Far detector mass (kton)	Beam Power (MW)	Nominal years of data taking (yr)
1	1	1	1
60	25	1.2	2
180	25	1.2	6
245	34	1.2	6
408	34	1.2	10
840	70	1.2	10

Table 1. Exposure for various configurations.

- **Mass hierarchy:** Matter effects grow quadratically with distance. The required exposure to reach a neutrino mass hierarchy determination with a 5σ C.L. or better with 50% probability (Delta chi^2_bar = 25) is plotted in Figure 1. The required exposure for a 3σ C.L. or better with 50% probability (Delta chi^2_bar = 9) is found by rescaling.

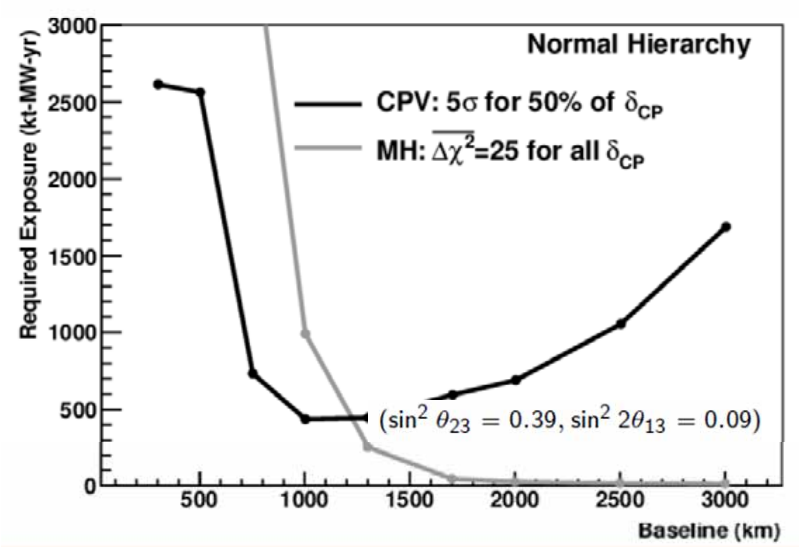

***Figure 1**: required exposure for CPV and MH as a function of baseline (km).*

- MH sensitivity depends strongly on the baseline. To reach Delta chi^2_bar = 25 requires an exposure of 245 kt.MW.yr (34 kton, 1.2 MW, 6 years) at 1300 km and 50 kt.MW.yr (20 kton, 1.2 MW, 2 years) at 2300 km.

- It is likely that reactor experiments (e.g. JUNO) and atmospheric measurements (e.g. INO, PINGU, HyperK) will have difficulties in reaching a sensitivity of Delta chi^2_bar = 25. In the end, only LBNF can give such a measurement.

- Hence, the competitiveness to determine MH, compared to reactors and atmospheric experiments, is defined by the ability to reach delta chi^2 = 9 (data) <u>first</u>.

- To reach Delta chi^2_bar = 9 requires an exposure of 90 kt.MW.yr (= 25 kton, 1.2 MW, 3 years) at 1300 km and 18 kt.MW.yr (= 5 kton, 1.2 MW, 3 years) at 2300 km.

- To match these goals in a timely fashion, the initial fiducial mass should be 25 kton at 1300 km and 5 kton at 2300 km.

- **CPV:** The ability to discover CPV depends mildly on the distance compared to MH. In the initial phases, it is dominated by statistics. It also depends on the ν/νbar running mode.

- A 1300 km baseline and 50%-50% sharing is slightly better than at longer baselines in NH, more so in the IH case. The main reason is that the 1300 km has more events. At longer baselines (e.g. 2300 km), a 75%+25% running is better than 50%+50% running. At 1300 km, 50%+50% running is better than 75%+25% running.

- The 1300 km baseline has a coverage on the 1st oscillation maxima. The sensitivity comes mostly from the ν/νbar asymmetry. The 2nd oscillation maximum does not play an important role.

- A 2300 km baseline has better coverage of the 2nd oscillation maxima, due to a wider energy coverage. The 2nd oscillation maximum plays an important role in CPV. The sensitivity comes mostly from the spectral information.

- The spectral information method is more robust against signal normalisation uncertainties than the ν/νbar asymmetry. Systematic errors on normalisation of 1%+5% (signal+background) at 1300km are required to yield similar sensitivities as 3%+10-20% for signal+background at 2300km.

- The CPV goals can be reached in two independent way: (a) focusing on the ν/νbar asymmetry at 1300 km baseline, which is similar to the HyperK approach. (b) measuring the spectral information at longer baselines, which is fully complementary to the HyperK approach.

- More work is needed to assess the validity of the assumptions on systematic errors.

- The initial fiducial mass to address CPV should be at least 25 kton, regardless of the baseline.

6. Science staging and early start with a Pilot detector:

- The full science would require an initial mass of 25 kton to be commissioned around 2025.

- The execution of a "Pilot" of the size of 5 kton on a timescale of 2020 could establish LBNF as a key player in the deep underground non-accelerator physics field.

- A Pilot would test many aspects of the underground location, and provide an early physics programme. Its necessity might be implied in the P5 report by the statement "*The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.*"

- The Pilot will foster the creation of a community with the expertise that is needed for LBNF.

- An early long-baseline programme with a Pilot at a distance of at least 2000 km and a powerful beam would provide an option to address MH.

7. Implementation and requirements:

- The science strategy and a project plan with identified resources will be developed in two steps: a LOI and a proposal.

- Working towards a plan, matching scientific ambition and realism, is a process that involves two main actors liaising with their respective funding agencies:
  (a) The Hosting Laboratory (HL)
  (b) The International Collaboration (IC)

- IC and HL develop together the final configuration parameters.

- The HL is responsible for the definition of the facility, comprising:
  (a) a high power neutrino beam,
  (b) a near infrastructure for detectors and beam monitors,
  (c) a far infrastructure for large deep underground detectors.

The process is "top-down". The the far site is selected and managed by the HL.

- The IC is responsible for the definition of:
  (a) the near detector(s),
  (b) the far detector(s).

The process is "bottom-up".

- Signatories of the LOI express a commitment to define and decide upon scientific priorities and strategies and the configuration parameters. It might be possible to decide on some of these before the LOI submission.

8. Additional input and external actions:

- A global combination of neutrino oscillation results can help determine MH and CPV, and exclude regions of the parameter space. Present data from T2K and reactors disfavour the region $\sin\delta>0$. The running programmes (T2K, NOvA, and reactors) are expected to provide significant new data in the coming years, improving such constraints. It is however expected that the statistical evidence in the end will remain limited (at most $\approx 2\sigma$ for excluding the wrong MH and $\approx$90%C.L. for $\sin\delta\neq 0$.), and not competitive with the goals of LBNF.

- LBNF will update its “wish-list” for the SBN programme.

- LBNF will develop a “wish-list” for CERN WA’s and neutrino platform programmes.

- CERN NA61 is a potential location to perform dedicated hadron-production measurements.

- NUSTORM is a potential experiment to execute dedicated measurements of the νe cross-section.

9. Final words:

- The scientific impact of LBNF will be strongly dependent on the possibility to timely install and commission a very massive far detector. An attractive science programme likely requires an initial mass of 25 kton around 2025. A well-developed and prioritised plan to achieve this target is needed.

- A Pilot project with a timescale <10 years could test many aspects and retire several risks, providing an early physics programme.

- LBNF should become the world class experiment that “everybody wants to do”.